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Revealing the Population of Isolated, Massive Stars in the Central Molecular Zone

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Abstract. We report on the current census of isolated massive stars in the Galactic center region, including recently discovered objects. The latest discoveries were selected for their hard X-ray counterparts, detected with the Chandra X-ray Observatory; or for their Paschen-α emission-line excess, detected in narrowband images with *HST/NICMOS*. The confirmed stars span a wide range of massive star evolutionary stages: OIa, Of, Ofpe, LBV, WNh, WN, WNE, WC, and WCd. We suspect that the majority of the hard X-ray-emitting, massive stars we have identified are colliding-wind binaries, although some may be HMXBs. Most of the confirmed massive stars have no obvious association with the known, young stellar clusters, but some may have escaped from them. Extrapolation of their numbers suggests the existence of a massive star population, comparable in size to that contained within the clusters collectively, which could account for the integrated far-IR luminosity emerging from the central half-kiloparsec. This additional massive-star population may have been supplemented by the tidal disruption of stellar clusters, or suggests an alternate mode of isolated massive star formation operating in the Galactic center region. Future experiments will constrain their kinematics, binary characteristics, and mode of formation.

1. Introduction

The Central Molecular Zone of the Galaxy, which encompasses the inner half-kiloparsec, is host to a plethora of high energy phenomena, much of which is driven by the formation, evolution, and death of massive stars. The prevalence of massive stars in the Galactic center region is not surprising, given the physical conditions of the environment. The region boasts the highest star formation rate density in the Milky Way ($\sim 10^{-7}$ $M_\odot$ yr^{-1} pc^{-3}; Figer et al. 2004), owing to the immense reservoir of molecular gas that defines the Central Molecular Zone (CMZ; e.g., see Morris & Serabyn 1996). This material is dense, hot, and under high tidal stress, when compared to molecular clouds elsewhere in the Galactic disk. Massive stars are forming vigorously in the CMZ, as evidenced by dozens of ultra-compact H II regions (particularly near the Sgr B cloud; e. g., see dePree et al. 1998), and three extraordinary, young stellar clusters that are among the most massive and dense in the Galaxy: the Arches and Quintuplet (Nagata et al. 1995; Cotera et al. 1996, Figer, McLean & Morris 1999; Figer et al. 2002), and the Central parsec cluster (Krabbe et al. 1995). These clusters are rich in Wolf-Rayet stars and O supergiants (WR/O), objects which have a profound influence on the dense Galactic center medium through intense UV radiation, supersonic winds, and supernovae. Although the majority of the known massive stars in the CMZ appear to reside within the known clusters, observations have unveiled a significant population of apparently isolated objects scattered throughout the CMZ. A handful of isolated WR/O stars were first identified by Cotera et al. (1999) and Homeier et al. (2003); a few of these have been associated with compact H II regions, while others cannot be tied to known stellar associations. With the small size of this earlier sample it was difficult to gauge the importance of this population of massive stars and make sense of their origin and overall distribution. Fortunately, recent wide-field surveys of the CMZ at infrared and X-ray wavelengths have opened a large window on the region, revealing a significant population of isolated WR/O stars and binaries whose distribution have important implications for the mode of massive star formation in the CMZ, the dynamical evolution of starburst clusters, and the large population of compact remnants that are concentrated near the Galactic center.

2. Surveys

2.1. Finding Massive Stellar X-ray Sources with *Chandra*

The Galactic center harbors the largest concentration of X-ray sources in the sky. A total of 9017 X-ray sources have been detected in multiple deep observations of the central $2^\circ \times 0\overset{\circ}{.}8$ (l, b) of the Galaxy with the *Chandra X-ray Observatory* over the past decade (Muno et al. 2009). Most of these sources ($\approx$6800 of them) are highly absorbed by interstellar gas and dust, indicative of distances near the Galactic center ($D \approx 8$ kpc; Reid 1993). According to Muno et al. (2003, 2009), the majority these objects are likely to be low-mass cataclysmic variables (CVs). However, the presence of at three starburst clusters implies that the products of massive star evolution must also contribute to the region's population of X-ray sources. The *Chandra* survey is sensitive to a subset of WR/O

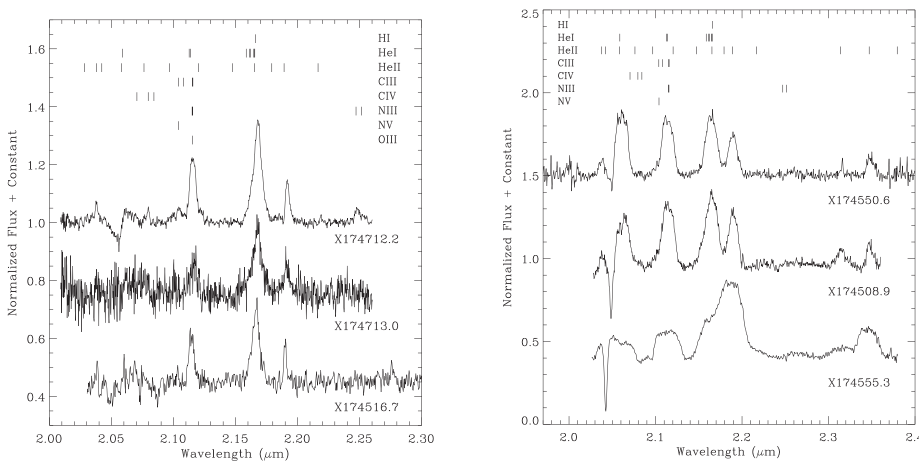

Figure 1. Example K-band spectra of hydrogen-rich (WN7–8h; *left panel*) and hydrogen-poor (WN5-7; *right panel*) WR X-ray sources from Mauerhan et al. (2010a). Broad emission lines of He I and He II dominate the spectra.

stars that are able to generate a relatively high flux of photons with $E > 2$ keV, such as colliding-wind binaries (CWBs) and accretion-powered high-mass X-ray binaries (HMXBs). The hypothesis of a CV dominated population is supported by the infrared studies of Mauerhan et al. (2009), who determined that only $\approx 6\%$ percent of the absorbed X-ray sources have reddened infrared counterparts brighter than $K_s = 15.6$ mag from the SIRIUS survey (see Nishiyama et al. 2006 and references therein for a description of SIRIUS). Nonetheless, we have determined that on the order of 100 of the X-ray sources have infrared counterparts with $K_s < 12.5$ mag, after correcting for the frequency of random X-ray/infrared matches. This brightness range is consistent with that of WR/O stars located near the Galactic center. Several WR/O star counterparts to X-ray sources in the central $17' \times 17'$ field around Sgr A* were identified (see Muno et al. 2006a; Mikles et al. 2006; Mauerhan et al. 2007) using earlier X-ray catalogs (i.e., Muno et al. 2003, 2006b). The deep, wider-field X-ray survey of the central $2^\circ \times 0\overset{\circ}{.}8$ (l, b) by Muno et al. (2009), and the associated catalog of infrared counterparts by Mauerhan et al. (2009), have paved the way to identify massive stellar X-ray sources and X-ray binaries throughout the greater CMZ.

We undertook an extensive infrared spectroscopy campaign to identify the spectral types of the most promising X-ray/IR matches within the catalog of Mauerhan et al. (2009); i.e., the brightest infrared counterparts with the smallest X-ray positional errors. Various facilities were utilized, including CTIO/SOAR, UKIRT, IRTF, the AAT, and Keck. As of late, we have spectroscopically confirmed 17 new massive stellar counterparts to the X-ray population, including hydrogen-rich and hydrogen-poor nitrogen-type (WN) WR stars, carbon-type (WC) WR stars, and O supergiants (Mauerhan et al. 2010a). Several examples are presented in Figure 1. These 17 discoveries increase the total sample of massive stellar X-ray sources in the Galactic center region to 30 (possibly 31), including those within the Arches and Quintuplet clusters. For the majority of these sources, the X-ray photometry, presented in Figure 2, is consistent with emission from thermal plasma having temperatures in the range of $kT = 1$–8 keV ($kT > 2$ keV for most of them) or non-thermal emission having power-law indices in the range of $-1 < \Gamma < 3$, and X-ray luminosities in the range of $L_X \sim 10^{32}$–10^{34} erg s^{-1} (0.5–8.0 keV). Several sources have exhibited long-term X-ray variability of a few factors between individaul X-ray observations. These X-ray properties are not a ubiquitous feature of single massive stars but are typical of massive binaries, in which the high-energy emission is generated by the collision of supersonic winds, or by accretion onto a compact companion. The detection of CWBs would not surprising in a region rich so with massive stars and clusters. The existence and detectability of HMXBs is less certain, although Pfahl et al. (2002) have suggested that on the order of hundreds of wind-accreting HMXBs might populate the region and be detectable X-ray sources. However, without direct evidence for binarity in these X-ray emitting WR/O stars, the possibility of intrinsic hard X-ray generation from single WR/O stars cannot be completely ruled out.

The case for binarity is strong, however, in three WC9 stars which exhibit relatively weak emission lines in their near-infrared spectra and strong mid-infrared excess in their SEDs, shown in Figure 3. These features were interpreted by Mauerhan et al. (2010a) as evidence for the presence of a hot dust component, making these WC9d stars. Non-dusty WC9 stars do exhibit infrared excess via free-free emission from their ionized stellar winds, although it is significantly weaker than the thermal dust emission. Hot dust is commonly associated with WC+OBI CWBs containing WC stars, where the dust is thought to be produced as the result of the collision between the carbon-rich and hydrogen-rich winds of the respective WC and OB stars (e.g., see Williams et al. 2005 and references therein). The hot dust emission, and perhaps continuum flux from the bright OBI companion, provides a natural explanation for the diluted emission lines in the infrared spectra of these stars. The Quintuplet proper members (DWCL stars; see Figer et al. 1999 and references therein) are extreme examples of this, exhibiting completely featureless spectra (see spectrum of star X174645.2 in Figure 3, left panel) and extremely large infrared excess (see SED of qF231 in Figure 3, right panel). One of our new WC9d stars, CXO J174519.1−290321, is a member of the Quintuplet, lying on the fringes of the known extent of the cluster. The other new WC9d discoveries lie in regions well outside of the known clusters; their origins are less certain (see Mauerhan et al. 2010a for more detailed information on locations of these stars).

2.2. Finding Emission-line Stars with *HST/NICMOS*

A Paschen-α (Pα) narrowband imaging survey of the Galactic center region was recently performed by Wang et al. (2010) using the *Hubble Space Telescope* and the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS). The survey covered a total projected area of 2253 pc^2 in 144 orbits of observations. The NIC3 camera was utilized and narrowband images were obtained through the F187N (line; λ1.87 μm) and F190N (continuum; λ1.90 μm) filters. Dozens of unidentified point sources of Pα line excess were discovered in the survey area, many of which are scattered through the inner 50 pc (Dong et al. in prep). The

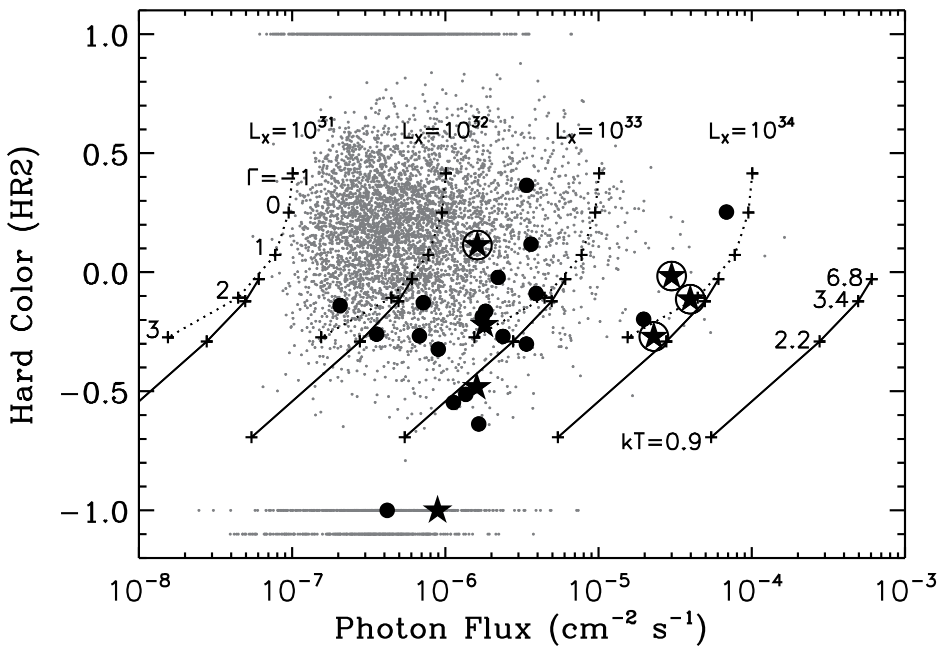

Figure 2. Photon flux vs. hard X-ray color (HR2) comparing massive-star counterparts (*large symbols*) to the field population of CVs (*small points*), from Mauerhan et al. (2010a). Sources associated with the Arches (*filled stars with circles*) and Quintuplet (*filled stars*) clusters are also included for comparison. Model tracks of thermal and non-thermal plasma absorbed by a hydrogen column of $N_{\rm H} = 6.0 \times 10^{22}$ $\rm cm^{-2}$ are plotted for comparison. The figure indicates that the majority of massive X-ray emitting stars have luminosities of $L_{\rm X} \approx 10^{32}$–$10^{34}$ erg $\rm s^{-1}$ (0.5–8.0 keV).

Pα sources with the brightest K_s-band counterparts ($K_s \leq 12$ mag) from the *Two-Micron All Sky Survey* (2MASS) were targeted for infrared spectroscopy using CTIO/SOAR, the AAT, and IRTF. We have currently identified nearly 20 additional isolated massive stars, including O, WN, WC, and Be/B[e] spectral types. One particular Be/B[e] type star, which we named G0.120−0.048, lies at the center of a circular nebula of Pα emission, shown in Figure 4. The nebula has no counterpart in the adjacent F190N continuum or at *Spitzer*/IRAC wavelengths. The spectrum of the star is similar to that of the Pistol Star, a luminous blue variable (LBV) of the Quintuplet cluster. Moreover, G0.120+0.048 was catalogued as a variable in Glass et al. (2001), exhibiting brightness variations having a higher amplitude than those of the Pistol Star during the same several years of monitoring. Thus we classify this star as a new LBV (LBV G0.120−0.048), and interpret the circular nebula surrounding it as a spherical shell of material ejected from the star within the last 10,000 years (see Mauerhan et al. 2010b for more details). The discovery of LBV G0.120−0.048 brings the

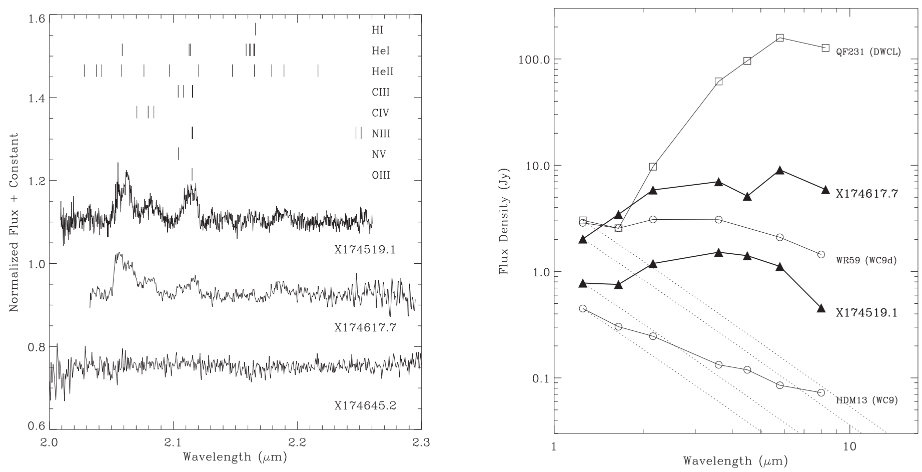

Figure 3. *Left Panel:* K-band spectra of X-ray emitting WC9d stars from Mauerhan et al. (2010a), including the DWCL star X174546.2 discovered by Hyodo et al. (2008). *Right panel*: Mid-infrared SEDs of the WC9d stars X174617.7 and X174519.1, shown with other WC9 and DWCL stars for comparison. The single non-X-ray-detected WC9 star WR59 exhibits weaker excess from free-free emission, while the extreme DWCL star qF231, an X-ray source, exhibits very strong excess from hot dust; X174617.7 and X174519.1 have excess between these two extremes, which is also likely to be from hot dust.

total number of known LBVs in the Quintuplet region to 3, the highest known concentration of these rare stars in the Galaxy. The other Pα discoveries, which include OB, WN and WC spectral types, will be presented in Mauerhan et al. (submitted).

3. Distribution, Origin, and Implications for Star Formation

Figure 5 exhibits the spatial distribution of the isolated massive stars discovered thus far in the Galactic center region, including discoveries from both the X-ray and Pα surveys. With the exception a few objects located near the outer regions of the Arches and Quintuplet clusters, most of the new stars appear relatively isolated or in loose associations. Seven hydrogen-rich WN and O stars are concentrated near the Sgr B H II region, which suggests that the Sgr B complex has been undergoing massive star formation for at least a few Myr. Several other WN and O stars, and a WC star, appear to be associated with the H1–H8 H II regions southwest of the Arches cluster. Other hydrogen-rich stars and more highly evolved hydrogen-poor WN and WC stars lie scattered within ≈ 50 pc, in projection, of Sgr A West; their origin, and relation to other massive stars in the region is unclear. It is possible that the relatively isolated stars originated within the clusters but were dynamically ejected via gravitational interactions

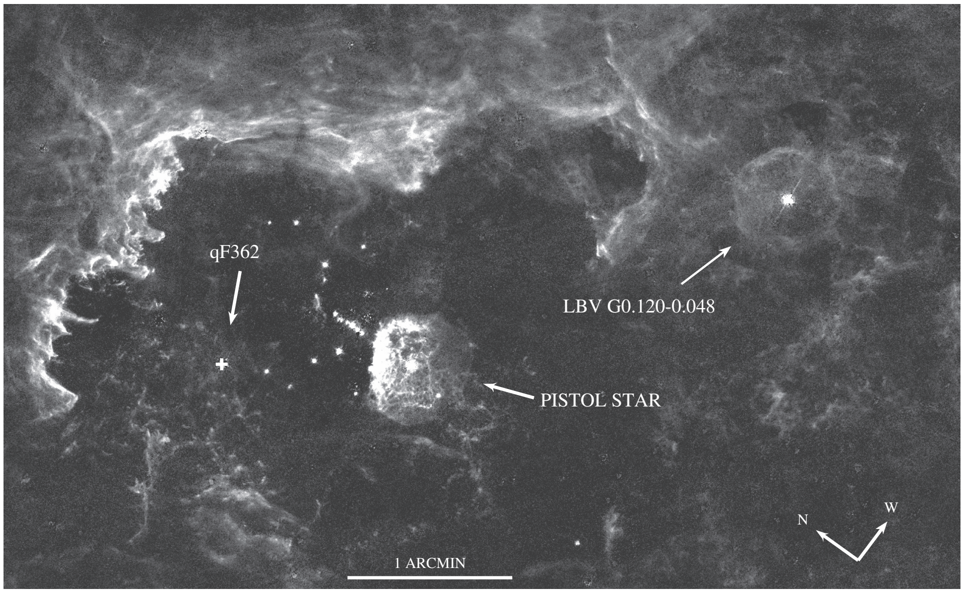

Figure 4. *HST/NICMOS* continuum-subtracted Pα survey image of the Sickle region containing the Quintuplet cluster, and the LBVs qF362, the Pistol Star, and the new discovery G0.120−0.048 (Mauerhan et al. 2010b).

with other massive stars and binaries in the cluster, or were ejected as the result of a companion supernova. Indeed, a noteworthy fraction of O stars (≈10–30%) in the Galactic disk are known to be runaways, ≈10% or more of which are binaries (Gies et al. 1986, 1987). Runaway WR+O binaries are also known to exist, such as WR 21 and WR 22 in Carina (Moffat et al. 1998). The strong tidal field at the Galactic center should amplify this process, since massive star and binaries whose cluster orbits are "heated" by gravitational encounters with other massive stars and binaries near cluster centers may drift beyond the tidal radius of a cluster (e.g., $r_{tide} \approx 1$ pc for the Arches cluster; Portegies-Zwart et al. 2001) and be stripped by the tidal field. Thus, massive stars and binaries should have escaped the Arches and Quintuplet clusters over their respective lifetimes of 1–2 Myr (Figer et al. 2002) and 4–6 Myr (Figer, McLean & Morris 1999). Indeed, there is some indication of a concentration of massive stars between the Quintuplet cluster and Sgr A West, and many of them may be escapees from the cluster. Proper motion measurements performed with adaptive optics, and radial velocity measurements from high-resolution infrared spectroscopy, could provide the kinematic information necessary to place meaningful constraints the origins of these isolated massive stars and their association with, or independence from, the stellar clusters.

Alternatively, some of the stars from our sample may be the products of a mode of isolated massive star formation, operating in tandem with the formation of dense stellar clusters. The relatively loose aggregations of early-O and WN stars near the H1–H8 H II regions southwest of the Arches cluster and near Sgr

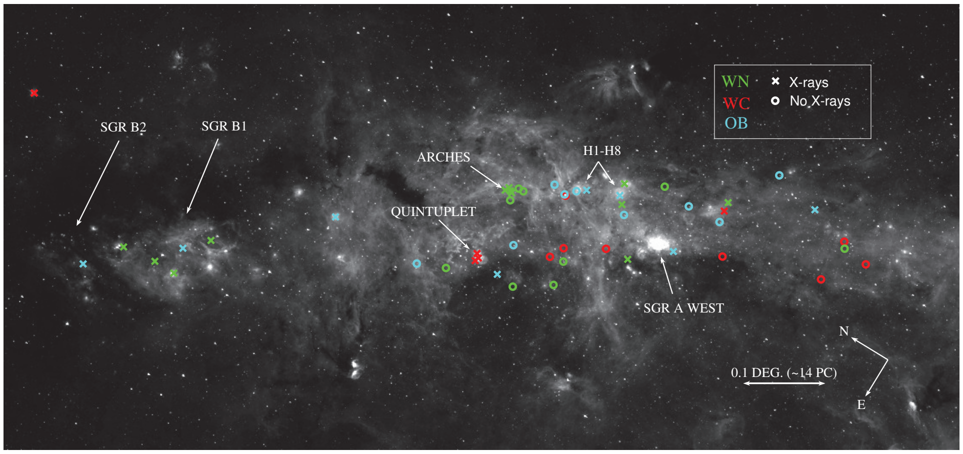

Figure 5. *Spitzer*/IRAC $\lambda 8\ \mu$m image of the CMZ, illustrating the spatial distribution of isolated massive stars, which are color coded according to spectral type. Cross points represent stars that have *Chandra* X-ray counterparts, which are likely to be close binaries. Circle points are not detected in X-rays. See Mauerhan et al. (2010a) for detailed information on spectral types.

B, and more highly evolved WN and WC stars that lie southwest of Sgr A West, might be the products of such a formation mode. However, it is also possible that some of these stars are members of stellar clusters that are less dense and massive than the Arches and Quintuplet, which have gone unnoticed because of confusion with the dense stellar background. Since clusters near the Galactic center are subject to strong tidal forces, which causes them to dissolve on a time scale of ~ 10 Myr (Kim et al. 1999), they may fade beyond detectability as a surface density enhancement within only a few Myr (Portegies-Zwart et al. 2001). Other, less dense systems might persist as undetectable entities for their entire lives. In those clusters, only the evolved massive stars whose strong winds will produce emission lines will be detectable via narrowband surveys like that of Wang et al. (2010). With respect to such a survey, a cluster that is relatively old ($\approx$ 6-10 Myr), or of lower initial mass and density than the Arches and Quintuplet, might only show a single, relatively isolated, emission-line point source, or a loose concentration of several point sources. This might be the case for some of the isolated massive stars shown in Figure 5.

Although the origin of the isolated massive stars in the Galactic center is puzzling, it is clear that significant massive star formation has been occurring in the CMZ, outside of the well known clusters, for several Myr, including the formation products of the Sgr B molecular cloud complex, the newly discovered regions southwest of Sgr A West, and the concentration of massive stars near the H1–H8 H II regions. The *Chandra* observations of the Arches and Quintuplet clusters indicate that only a small fraction of massive stars in the Galactic center are detectable as hard X-ray sources. Indeed, the Arches and Quintuplet contain over 100 massive stars each ($M > 20 M_{\odot}$), yet only several ($\approx 5\%$) are detected by *Chandra* as X-ray sources. If roughly the same fraction of the isolated massive stars is detectable in X-rays throughout the entire CMZ, then we speculate that the existence of ≈20 massive stellar X-ray sources outside of the stellar clusters implies the presence of ≈400 additional massive stars that have yet to be identified. Less than 10% of these will be in an evolved state, whereby strong emission lines will produced by stellar winds. The ≈15–20 non-X-ray detections from the Pα survey accounts for just under half of those expected; the remainder probably lie outside the Pα survey area, perhaps among the X-ray emitting stars near Sgr B, motivating an extension of the Pα survey out to Sgr B. Finally, it is noteworthy that the total inferred Lyman-α photon production rate that is required to explain the far-IR luminosity emerging from the central half-kiloparsec ($\sim 10^{52}$ photons s^{-1}) is about twice the amount generated by the three clusters collectively (Cox & Laureijs 1989, Figer et al. 2004); the several hundred massive stars implied to exist by the results of this work would account for the current deficit.

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